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Modelling Service Life and Life-Cycle Cost of Steel-Reinforced Concrete

Report from the NIST/ACI/ASTM Workshop held in Gaithersburg, MD on November 9-10, 1998

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Gary R. Bachula, *Acting Under Secretary for Technology*
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Ray Kammer, *Director*

The test methods to be recommended in 1999 will address: sampling and profiling; modelling and calibration; and determination of the chloride threshold for initiation of corrosion. The goal to be achieved in 2002 is a recommended international approach to modelling chloride penetration into concrete which can take into account all climates and environmental conditions. The Committee's state-of-the-art reports should be of particular interest to academics and testing laboratories, while its recommendations should be important to testing laboratories, practicing engineers, and standards bodies.

On behalf of Committee Chairperson, Carmen Andrade, Dr. Castellote invited other interested persons to join the RILEM Committee. (For those who may need it, Dr. Andrade's e-mail address is: Andrade@fresno.csic.es .)

2.2 MODEL FOR A QUANTITATIVE CORROSION DAMAGE FUNCTION FOR A REINFORCED CONCRETE MARINE SUBSTRUCTURE

Alberto Sagüés, University of South Florida

A damage function approach has been applied in predicting the course of corrosion in (mostly) marine structures. It has been applied in two ways [2,3], one simple and one more sophisticated. In the first, knowledge of the distribution of the thickness of the concrete cover over the reinforcing steel and of the surface chloride concentrations is used in calculations for each of three ranges of elevation with respect to sea level – the tidal zone, the lower splash zone, and the upper zone. Diffusion is assumed to be the only transport mechanism, and it is also assumed that each elevation has its own threshold concentration of chloride to initiate corrosion. From the results, if the cost of repair per unit area is known, the repair cost can be calculated. This model blends uncertainty with variability.

The first approach was used in forecasting the extent of corrosion of the reinforcement in two 31 year-old, parallel concrete bridges in a marine environment in northern Florida. A preliminary inspection showed that the chloride concentration at the depth of the reinforcement in the cylindrical piling was approaching the level normally associated with the onset of corrosion. Future traffic projections required deciding between alternatives that included expanding the present structures or rebuilding. To select the most appropriate alternative, an investigation was conducted to develop an approximate forecast of future corrosion development. The investigation included assessing the present condition, and developing a quantitative corrosion deterioration model. The corrosion condition was assessed by visual observation, direct examination of reinforcement, and electrochemical corrosion measurements. Chloride-penetration profiles were obtained from extracted concrete cores. Reinforcement cover was measured by direct observation. The chloride profile data were analyzed to obtain apparent chloride ion diffusivities, surface concentrations and bulk concentrations. The deterioration model used the statistical distributions of concrete cover, diffusion coefficient and surface concentration to estimate the distribution of times for corrosion initiation and appearance of external damage on the bridge substructure. The output of the model was a damage function indicating the amount and location of repairs needed as a function of bridge age.

The model outputs showed a period of no significant corrosion damage followed by gradual deterioration afterwards. The shapes of the curves for each elevation range reflect the assumed dispersion of model parameters (concrete cover, surface concentration, and diffusivity) around their average values. An assumption of no dispersion would have resulted in a sharp step damage function for each range, with damage starting at the time corresponding to that dictated by the average parameter values plus the assumed propagation time. The model outputs project that the most damage will take place in the tidal zone during the next few decades. Detailed cost estimates for rehabilitation were prepared based on the repair/rehabilitation alternatives considered.

The model is not an absolute prediction tool. It should be viewed as a means of providing quantitative projections to assist in comparing repair and future construction alternatives. The output is highly sensitive to the assumed values of key parameters, such as the chloride concentration threshold (C_T), which are subject to much uncertainty. The overall modeling assumptions involve numerous simplifications that ignore important issues such as effective diffusivity and surface concentration variations with time, the effect of chloride ion binding on diffusion, alternative chloride transport mechanisms, effect of potential on C_T, non-flat surfaces, and the factors altering the length of the propagation stage. Improvement is also needed to discern between actual variability and measurement uncertainty in the parameters (concrete cover, diffusivity, surface concentration) used as distributed values.

The second approach [4] is more complicated; it uses a propagation stage model that incorporates oxygen diffusion, corrosion, and a concentration- and potential-controlled threshold into computations of macrocell corrosion; it can take into account the effects of corrosion inhibitors and anodic protection. The approach includes a method of generating a quantitative corrosion damage function given the concrete properties, the configuration of the substructure, and basic assumptions about corrosion mechanisms. The output of the model is the amount of damage requiring repair at different elevations in the substructure as a function of time. The model is illustrated for a partially submerged marine substructure column. The damage function is developed for three sequential computational model modules concerning chloride ion transport, corrosion distribution, and evaluation of surface damage. The quantitative model output is illustrated for the different stages of deterioration of the system and for corrosion protection alternatives.

The entire system is initially considered to be in the passive state, and the open circuit potential is not a strong function of elevation. Chloride ions begin to penetrate to different extents at various elevations, depending on the local surface chloride content. The evolution of chloride concentration as a function of potential and time is calculated by means of a *chloride transport module* that assumes diffusional chloride transport. Eventually, the chloride threshold, C_T, is reached at an elevation where chloride accumulates rapidly and causes local depassivation of the steel. This, in turn, causes a local potential change, and formation of a corrosion macrocell that depresses potential at the active spot and in the passive steel nearby. The redistribution of potentials and resulting corrosion rates are calculated using a *corrosion distribution module* based on a previously developed computation methodology. Since C_T is potential dependent, steel depassivation is not likely to happen next at spots immediately adjacent to the region of potential depression, but rather at other places with the appropriate combination of sufficiently high potential and chloride contamination. Every time an additional spot becomes active, the potential distribution becomes readjusted and so does the C_T distribution. As each spot enters the active corrosion condition, the corrosion distribution module calculates the local corrosion rate. The rate is integrated as a function of time and converted into local corrosion penetration with a value M_{crit} assumed to result in concrete cover spalling for the combination of steel (rebar) diameter and concrete cover used at that location of the system. When M_{crit} is reached at a given element of the system, the element is declared damaged and its projected area on the external concrete surface counted as damaged area. The sum of damaged area for the entire system as a function of time is defined as the *damage function* of the system.

2.3 PRESENT LIMITATIONS IN SCIENTIFICALLY-BASED PREDICTION MODELS FOR CHLORIDE INGRESS INTO SUBMERGED CONCRETE

Lars-Olof Nilsson, Chalmers University, Sweden

Most current prediction models for chloride ingress into concrete are empirical and depend on fitting curves to measured chloride profiles. Since the models do not have firm physical and chemical foundations, predictions are made by extrapolation from existing data. The results of the extrapolations are uncertain because of large scatter in the data and uncertainties in the models. Chalmers University of Technology has developed scientifically-based models that use current knowledge of the physical and chemical processes involved in the transport of chlorides in concrete. They have concentrated mostly on chloride ingress and a little on the corrosion threshold. They have used a lot of literature data, some from people at the present workshop. The model runs in a WINDOWS environment.

This study described [5] had the objective of determining the possibilities and the limits of the Chalmers University (CTH) model for predicting the penetration of chloride ions into concrete. The diffusion of chloride is established from Fick's first law and a diffusion coefficient is determined by the CTH Migration Test. The effects of temperature, age of the concrete, and the variation of the diffusion coefficient as a function of depth have been examined. The interactions between chlorides and the concrete are represented as a function of concentration of free chloride, temperature, and pH of the pore solution. Leaching of alkalis is included in the model to predict the pH at different depths.

The results of the predictions for different cases have been compared with results of measurements made in the laboratory and the field. Differences between predictions and the results of accelerated immersion tests at elevated temperatures appear to be due to the fact that the diffusion coefficient depends on concentration. The effect of unsaturation of the submerged concrete is illustrated by some examples and its consequences are analyzed.

Predictive models that are described as "scientific" should be based on relevant and decisive physical and chemical parameters such as mass balance equations, a genuine flux equation, chloride binding relationships, the effect of material characteristics, and the effect of environmental conditions. Such a model, ***ClinConc***, has been developed by Tang [6]. Features of the model are: